

# **Multi-Scale Atmospheric Numerical Modeling for Planetary Applications**

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# Purpose

- single, common framework for local-to-global modeling
- maximum grid flexibility
- nesting
- fast, parallel architecture
- clean separation of model physics / dynamics from software “architecture” -
- minimal impact of platform changes
- model that can be “switched” from planet-to-planet with minimal impact

# Project

- Modify existing NCAR Weather Research and Forecast (WRF) model ([www.wrf-model.org](http://www.wrf-model.org))
- Change the grid discretization to allow for non-conformal (e.g. lat-lon) grids
- Implement polar boundary conditions to allow for global extent (basic WRF is limited area)
- Change “clocks and calendars” to allow for generalized orbits / planet spin rates
- Allow physical constants to be user-defined in a single location

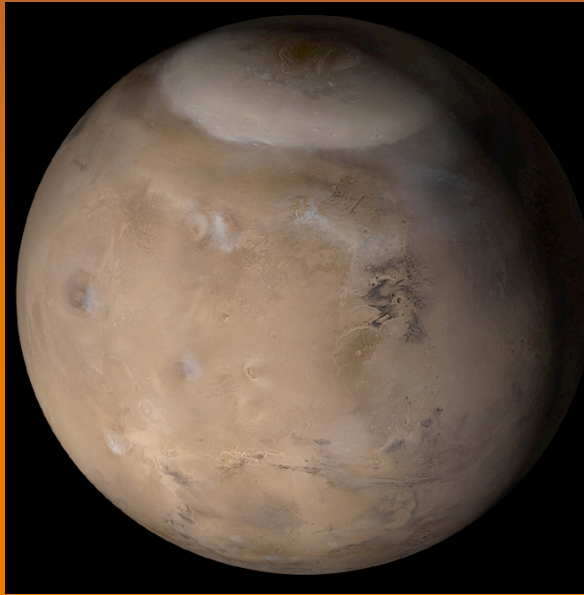
# Earth



$\text{N}_2$  atmosphere  
 $P_{\text{surf}} \sim 1 \times 10^5 \text{ Pa}$   
 $T_{\text{surf}} \sim 288 \text{ K}$

Water cycle  
Oceans & land surfaces

# Mars



$\text{CO}_2$  atmosphere  
 $P_{\text{surf}} \sim 610 \text{ Pa}$   
 $\overline{T}_{\text{surf}} \sim 210 \text{ K}$

Very eccentric orbit  
Major topography  
Dust storms

# Titan

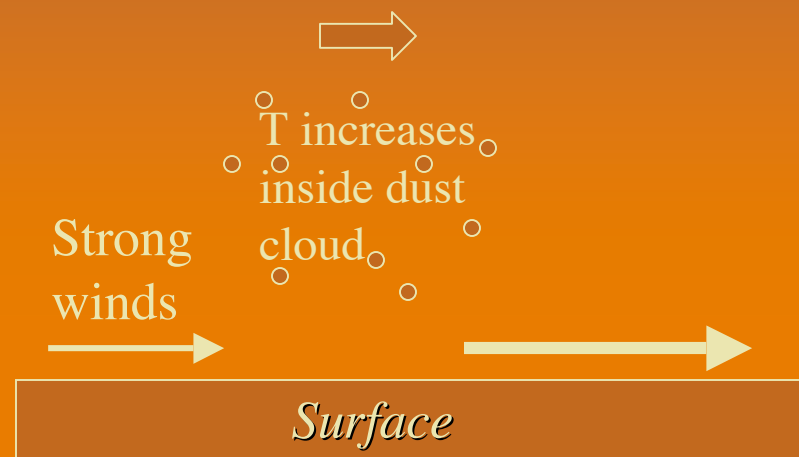


$\text{N}_2$  atmosphere  
 $P_{\text{surf}} \sim 1.5 \times 10^5 \text{ Pa}$   
 $T_{\text{surf}} \sim 93 \text{ K}$

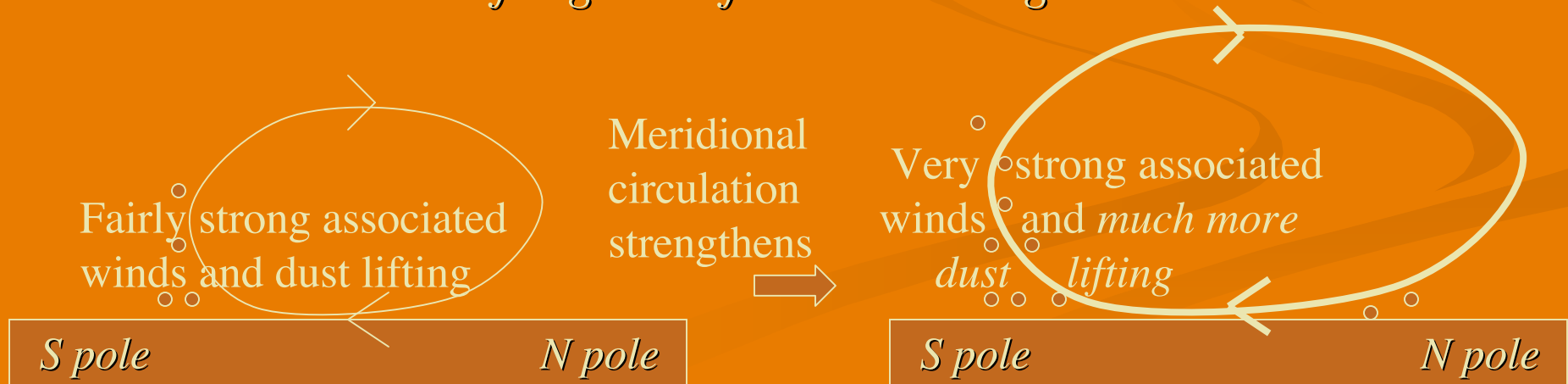
Thick haze layers  
Methane 'hydrology'  
Slowly rotating

# Storm onset & evolution: *multiscale* *feedbacks*

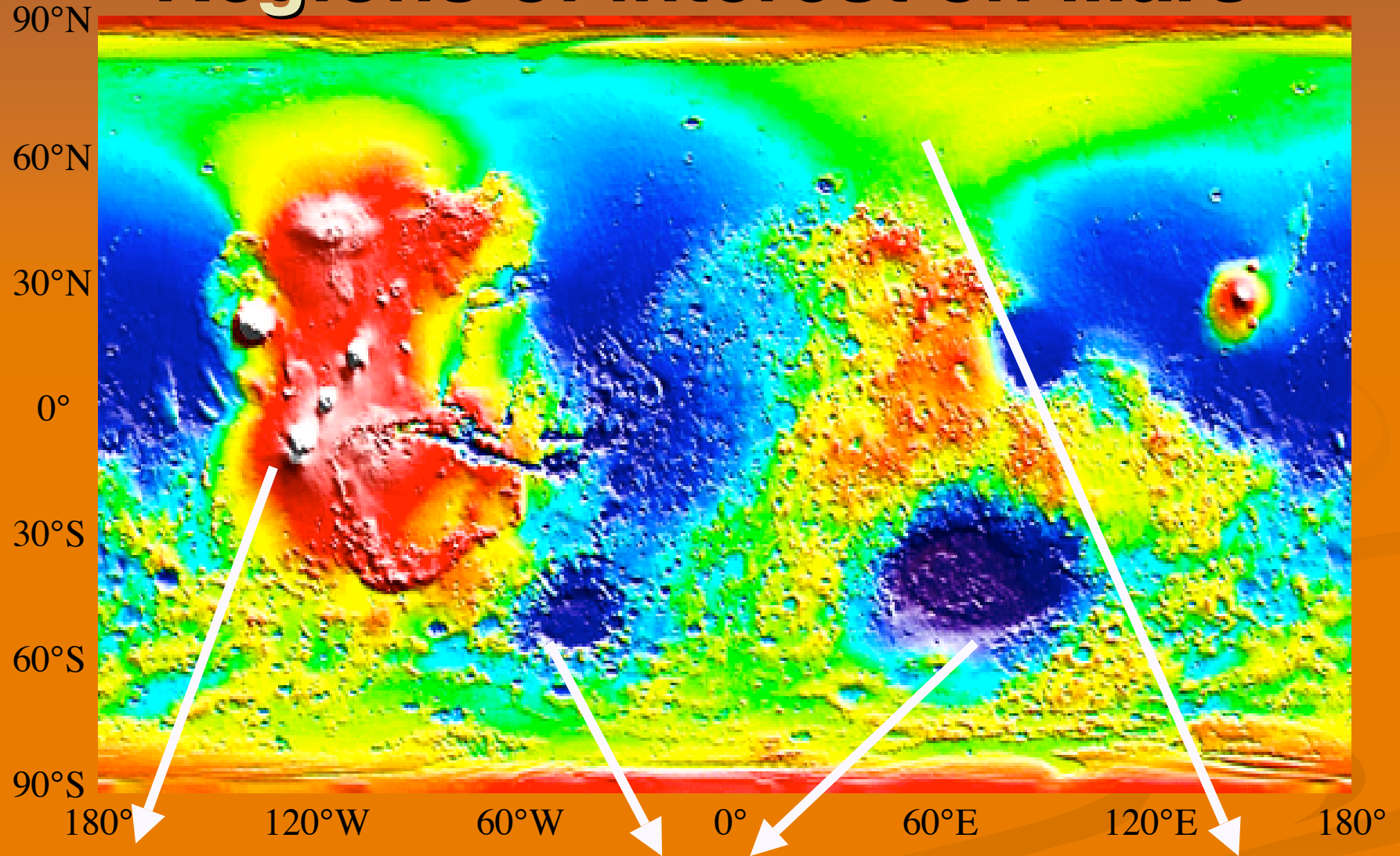
*Wind stress lifting: +ve feedbacks 1 - local scale*



*Wind stress lifting: +ve feedbacks 2 - global scale*



# Regions of interest on Mars



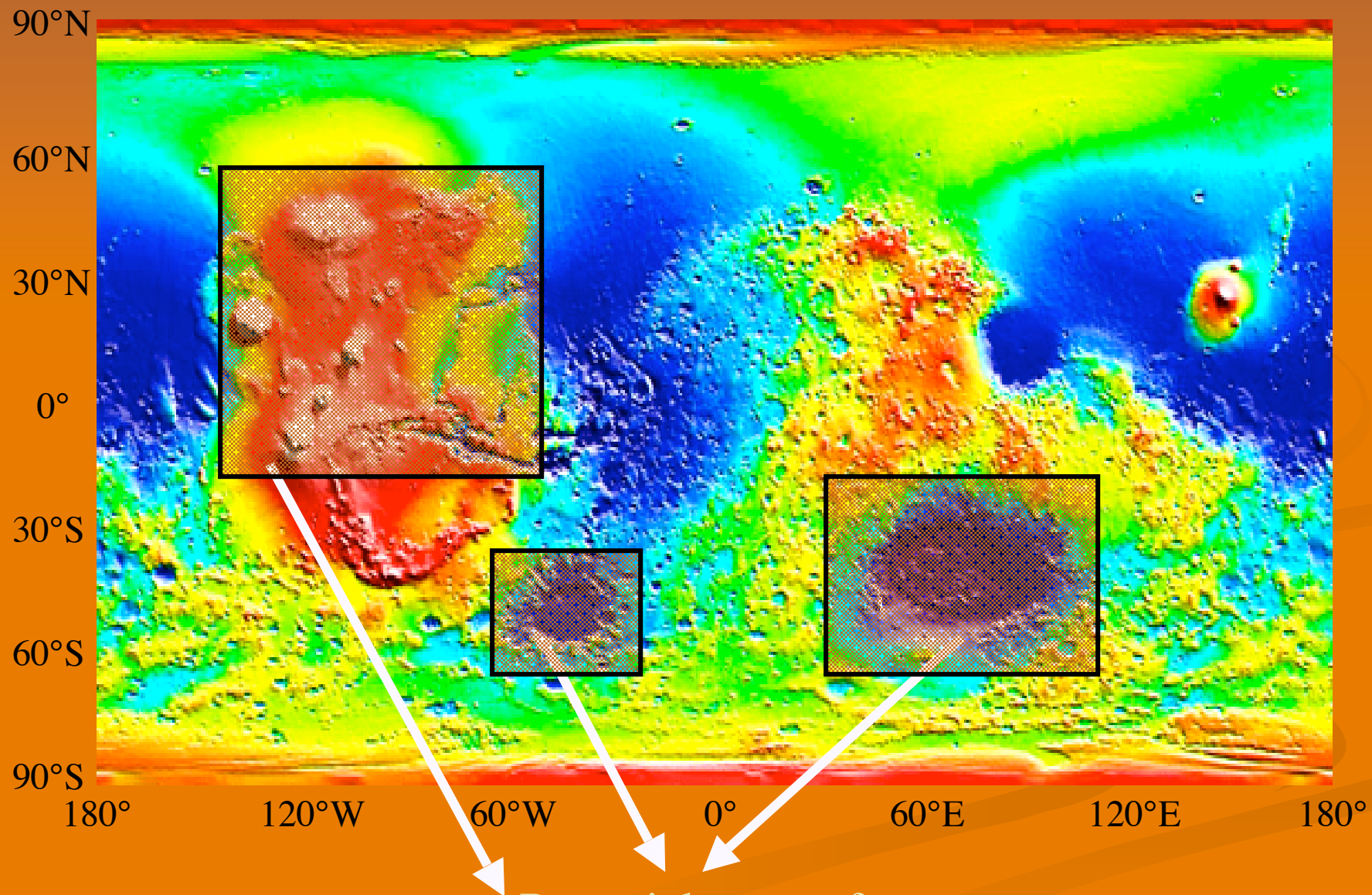
Tharsis: strong slope flows;  
Western boundary currents  
on the eastern edge

Argyre and Hellas: slope flows  
in region of strong zonal winds  
and near cap edge

Northern plains:  
relatively  
uninteresting



# Regions of interest on Mars



Potential areas of  
higher resolution

# The Weather Research and Forecasting (WRF) model

- Mesoscale (limited area) model for weather research and forecasting on Earth
- Developed by NCAR in collaboration with other agencies (NOAA, AFWA, etc.)
- ***Aim:*** to produce a reliable mesoscale model, to be used for real-time forecasting *and* as a research tool, with improvements being worked into new releases



# Features of WRF

- Dynamics conserve mass and angular momentum  
- highly accurate

- Highly parallel code  
=> efficient

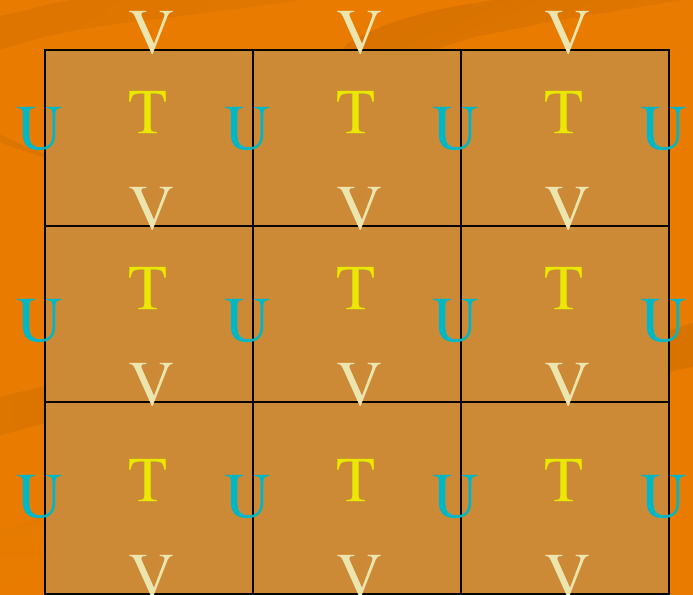
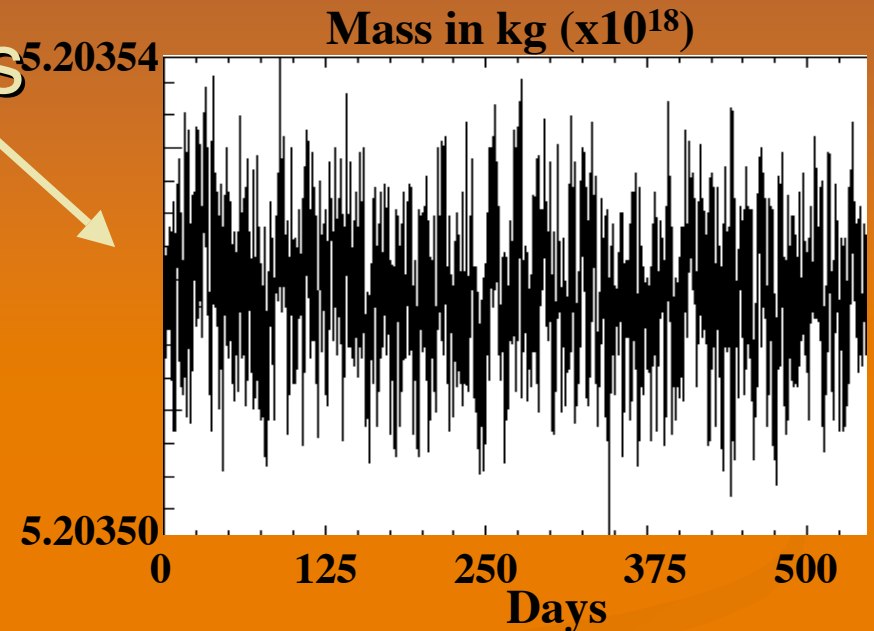
- Large suite of physics parameterizations and a modular form => flexible

- Uses Arakawa C-grid

U = zonal (E-W) velocity point

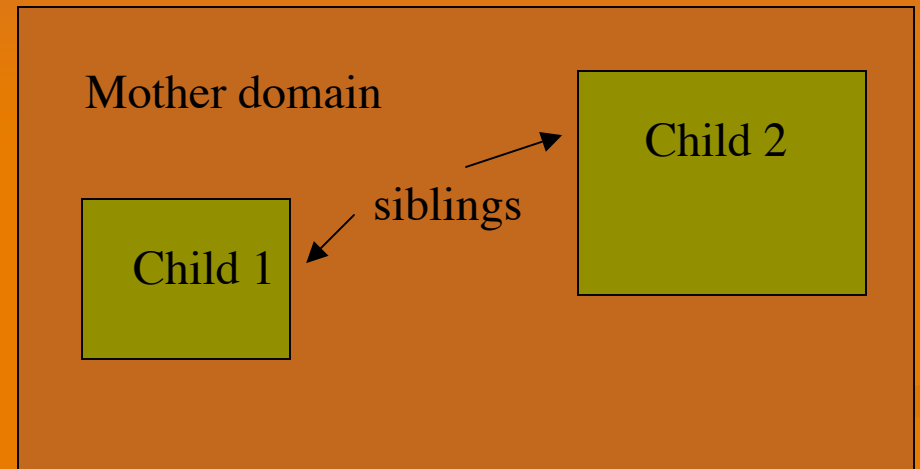
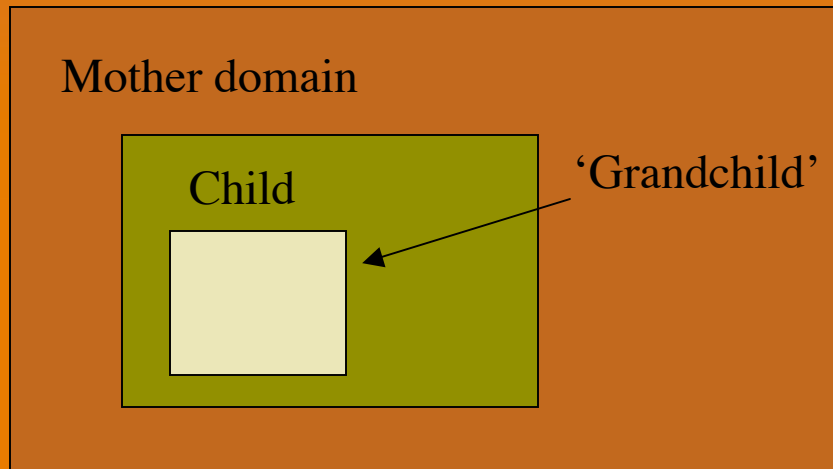
V = meridional (N-S) velocity point

T = temperature / mass point

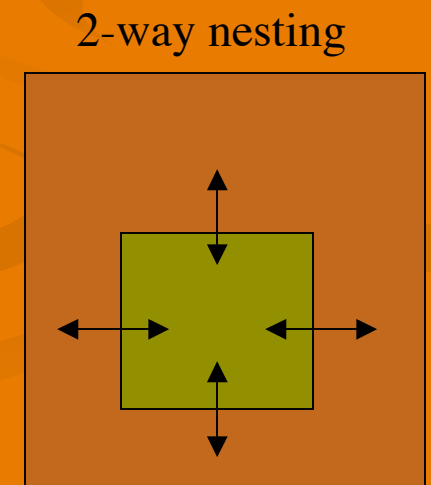
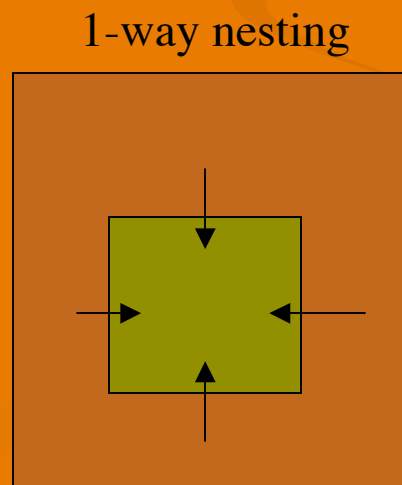


# Features of WRF (cont.)

## ■ Nesting capability:



## ■ 2-way nesting capability:



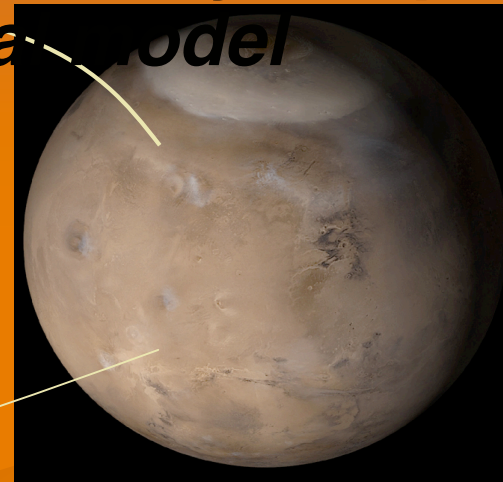
# The usual approach - how mesoscale WRF runs:

a) place nests within a *mesoscale model (WRF)*, with



WRF

b) its initial and boundary conditions being provided by a *separate global model*

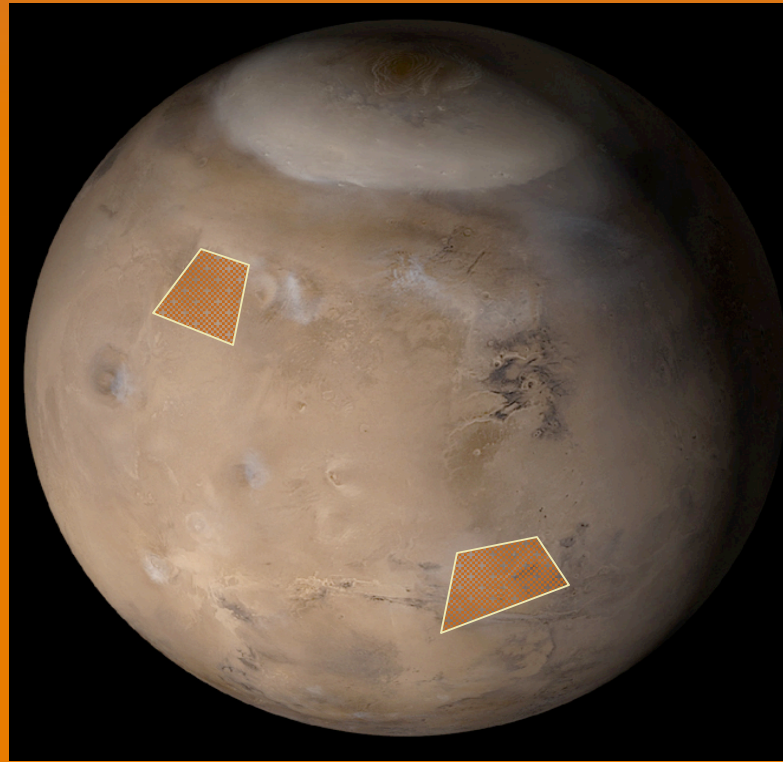


Separate global model

## Drawbacks:

1. Interface between global and mesoscale models is one-way => no feedbacks from small to larger scale
2. Unless specially designed to match, often have different dynamics and/or physics - *inconsistent*
3. Interface is also 'messy', e.g., must view output from the two models using different tools

Globalising WRF gives a highly *accurate & efficient global* model, in which we can place 1- & *2-way* nests

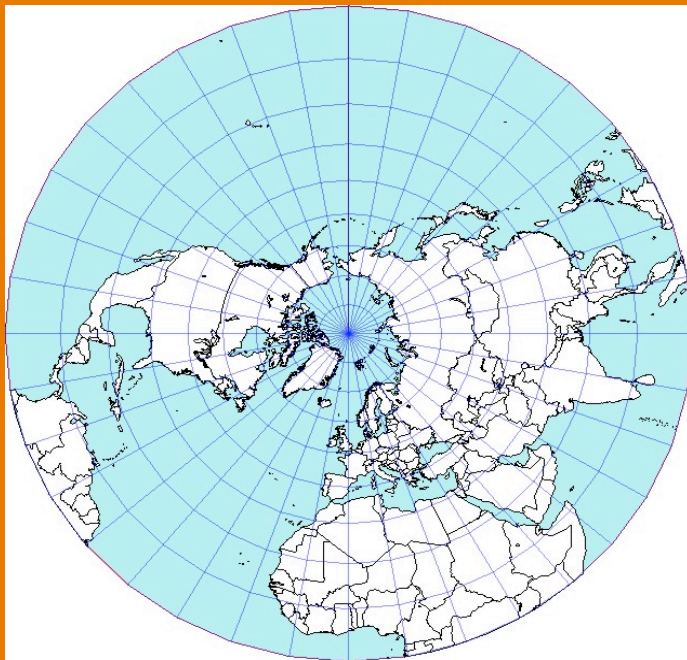


So we are basically using WRF's nesting abilities to *nest all the way down from global*

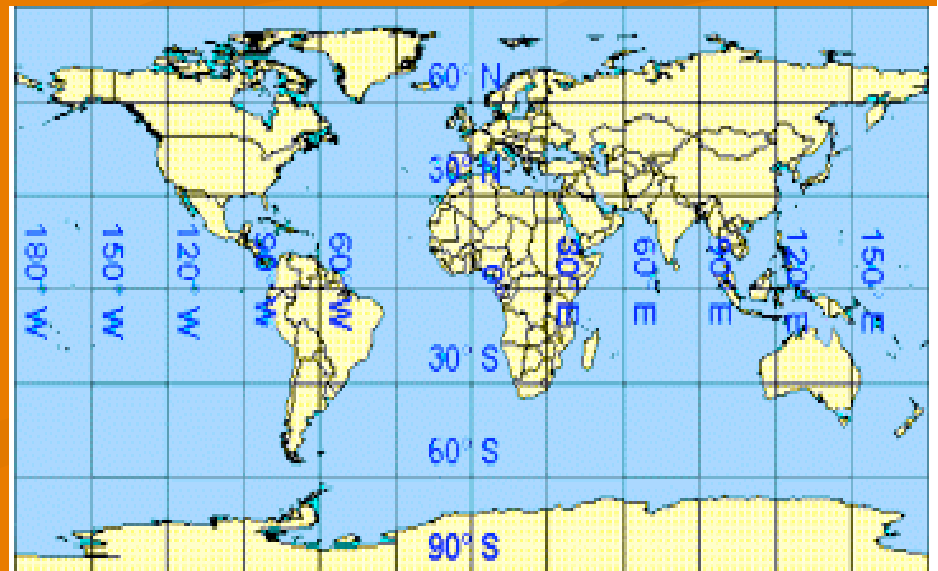
# Changes required for *global* WRF

- Allow use of a latitude-longitude grid

WRF is set up for *conformal* rectangular grids (such as polar stereographic) where the map to real world scaling factor is the same in the x as in the y direction



We still need a *rectangular* grid, but one which will reach *from the south to the north pole*  
=> lat-lon grid



If  $dx$  = gap between grid points in map coordinates,  
and  $dX$  = actual distance (in meters),  
then  **$dX = (1/m_x) dx$**  and likewise  **$dY = (1/m_y) dy$**

## Original WRF

Conformal grid  
 $\Rightarrow$  for all map projections  
available (mercator, polar  
stereographic, etc.),  
 **$m_x = m_y$  at all points**

$\Rightarrow$  Only one map scale  
factor ( $m$ ) used, and  
omitted altogether when  
 $m_x$  and  $m_y$  cancelled

## Global WRF

Lat-lon grid  $\Rightarrow x = a\lambda, y = a\phi$ ,  
 $\Rightarrow dx = a d\lambda, dy = a d\phi$ ,  
whereas  $dX = a \cos\phi d\lambda, dY = a d\phi$   
 $\Rightarrow m_x = dx/dX = \sec\phi, m_y = dy/dY = 1$   
 **$\Rightarrow m_x \neq m_y$**

$\Rightarrow$  Needed to identify which map scale  
factor was required in all equations  
where 'm' appeared, and reintroduce  
map scale factors where they previously  
cancelled (so were omitted)

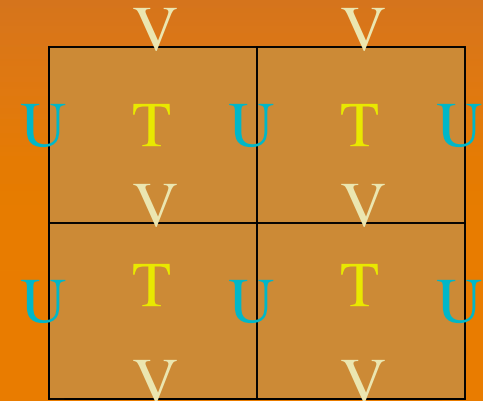


# Changes required for *global* WRF

## ■ Deal with polar boundary conditions

Place  $v$  points at poles, with  $v$  there  $= 0$

Nothing is allowed to pass directly over the poles  
- atmospheric mass is pushed around the pole in longitude instead - and no fluxes can come from the polar points when calculating variables



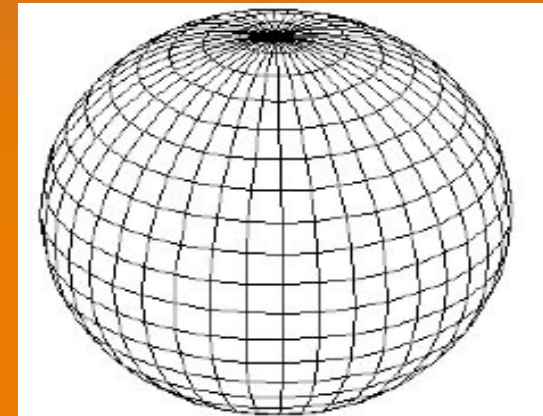
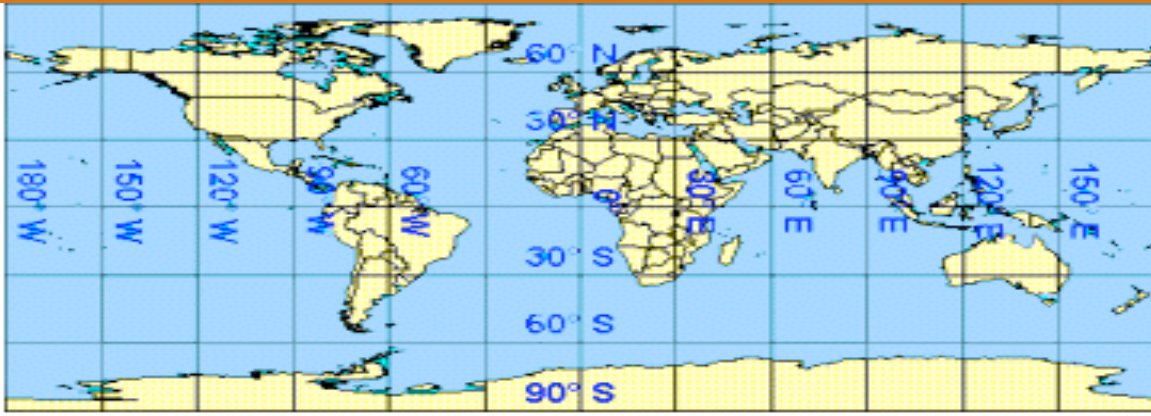
## ■ Deal with instabilities at the model top

The basic *mesoscale* WRF model generally only reached a maximum of ~30km, plus was regularly (and frequently) forced by a separate GCM

However, ‘standalone’ *global* WRF will develop upper level instabilities due to spurious wave reflection at the model top if these are not damped in some way - we must therefore introduce a ‘*sponge layer*’

# Changes required for *global* WRF

- Avoid instabilities due to E-W distance between grid points becoming small near poles



This is a problem due to the CFL (Courant Friedrichs Lewy) criterion:

$\Delta t \lesssim \Delta x / U$  where  $U$  is the fastest moving wave in the problem

$\Rightarrow$  As  $\Delta x \rightarrow 0$ ,  $\Delta t$  must  $\rightarrow 0$  also, which is very expensive

$\Rightarrow$  a) Use a small  $\Delta t$  (far less than needed to satisfy at the equator), **OR**

b) Increase largest effective scale  $\Delta x$  by filtering out smaller wavelengths (e.g. retaining only wavenumber 1 at the pole itself)

*Usual method in GCMs is to use a polar Fourier filter*

# Changes for *planetary* WRF

Models are generally *very* Earth-specific!

- Remove 'hardwired' planet-specific constants - instead use parameters which vary with planet
- Change 'Earth time' to 'general planet time'
- Allow orbital parameters to be specified
- Add physics parameterizations where needed

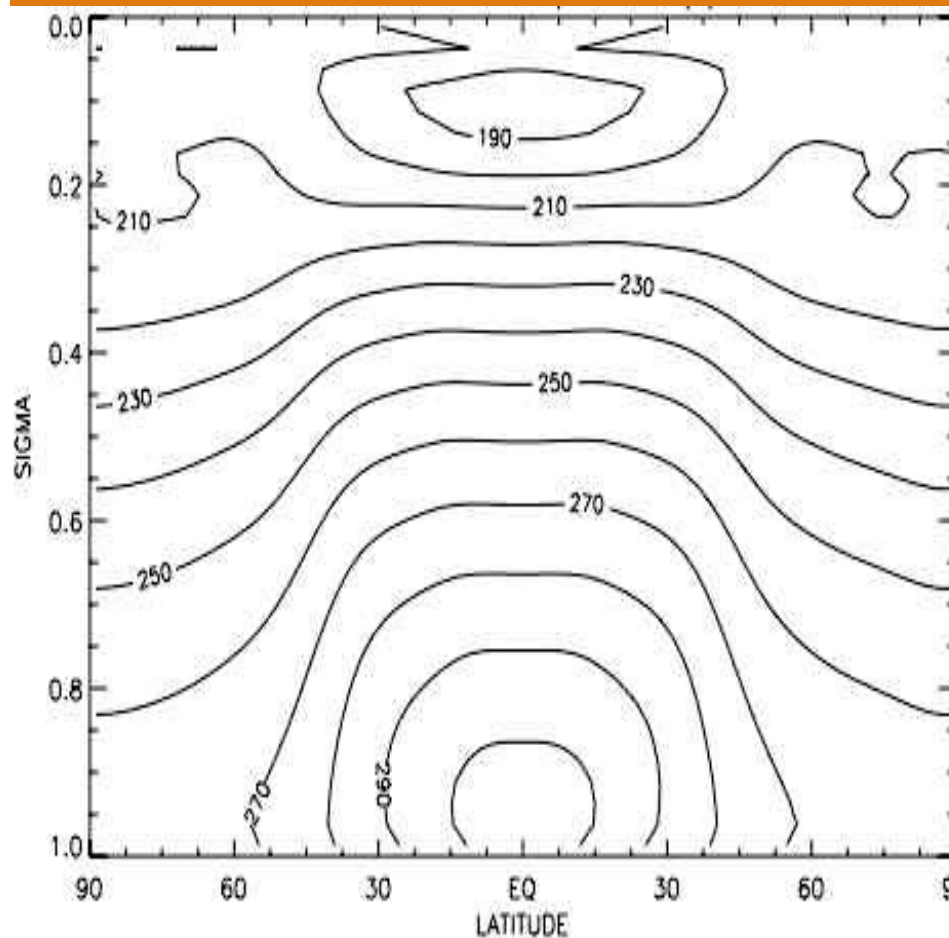
# Results: for Earth (up to 3.)

1. ***Solid-body rotation test*** (for a non-rotating planet!) including solid body rotation over the poles
2. ***Held-Suarez standard test of a dynamical core:***  
Newtonian relaxation to typical tropospheric temperature profiles with Rayleigh friction (winds slowed towards zonal mean) increasing with height
3. ***Polvani-Kushner extension to Held-Suarez:***  
added a simple stratosphere with cooling over winter pole
4. ***Further testing*** to look at wave propagation etc.

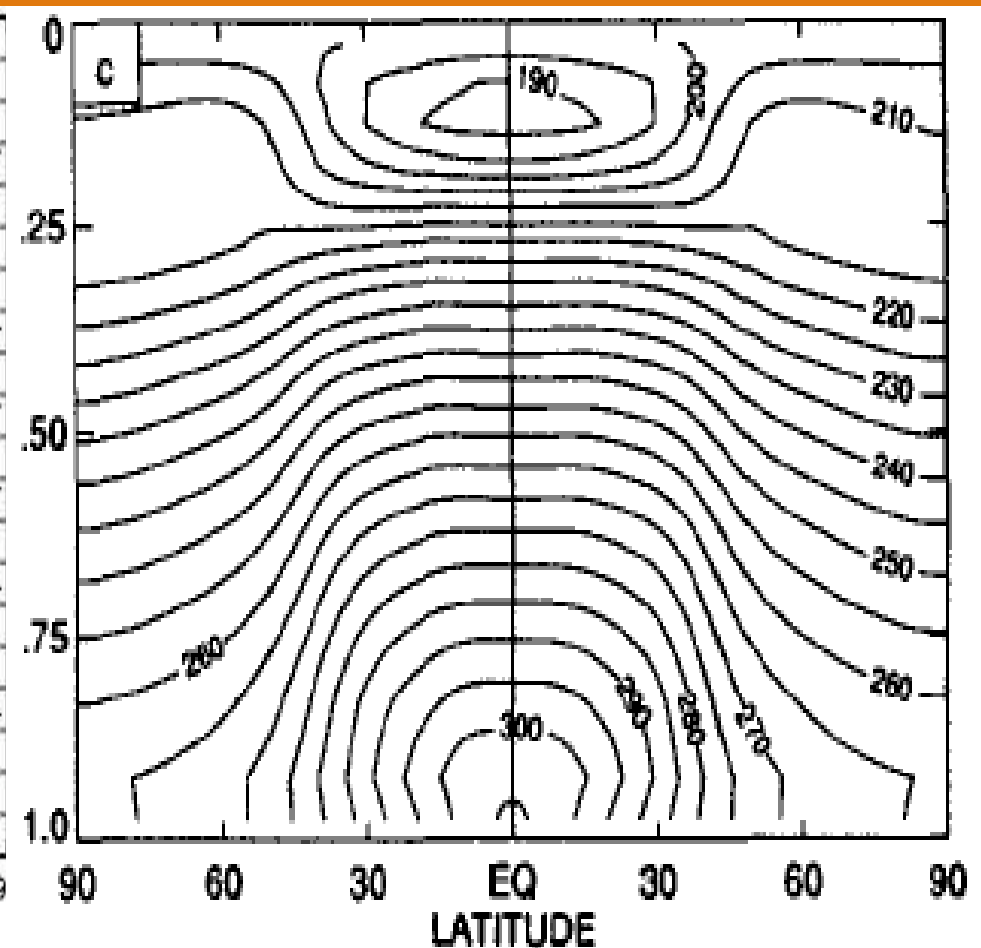
## 2. The Held-Suarez test:

a. Zonal mean T averaged over last 1000 days

Global WRF



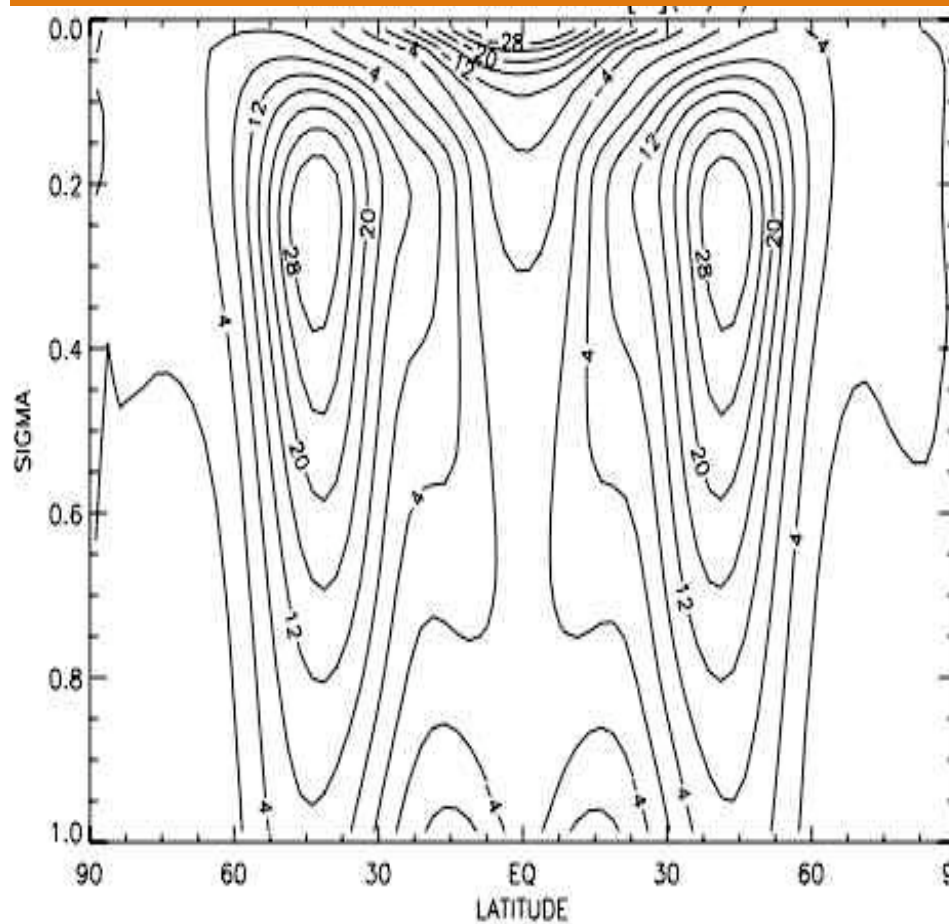
Expected result



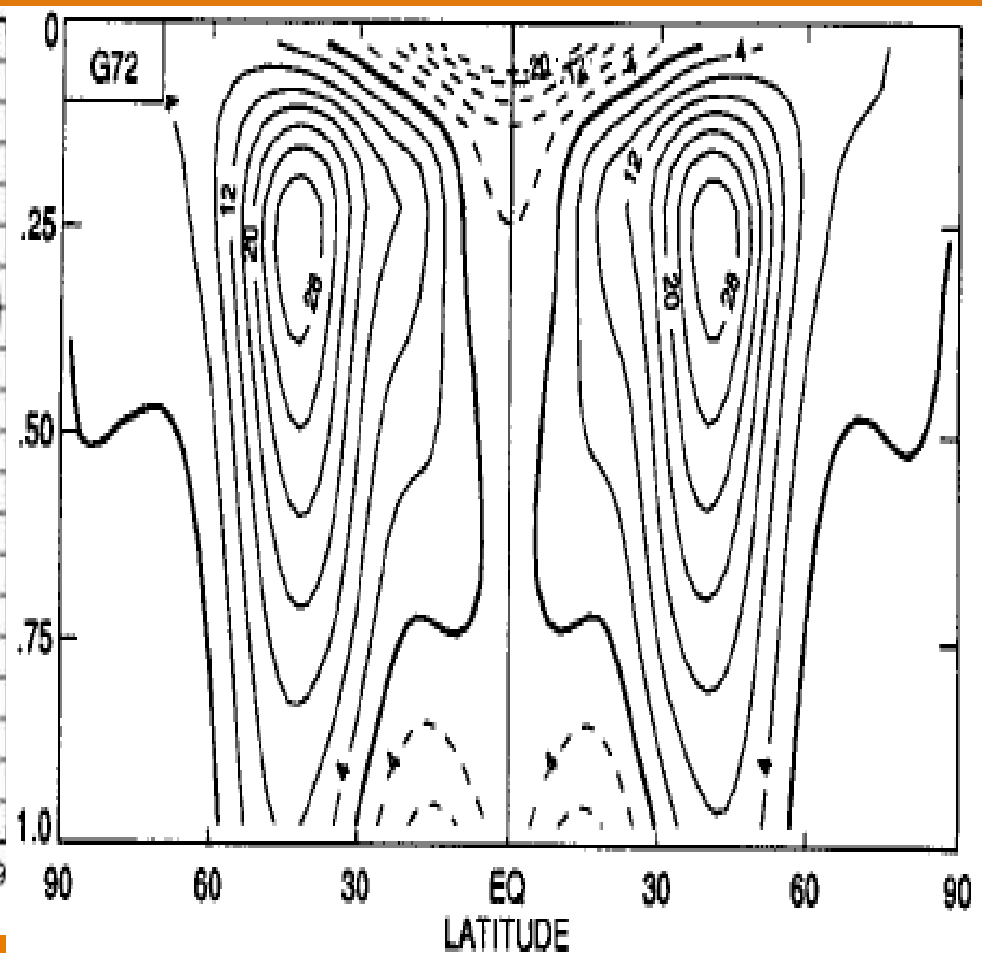
## 2. The Held-Suarez test:

b. Zonal mean u averaged over last 1000 days

Global WRF



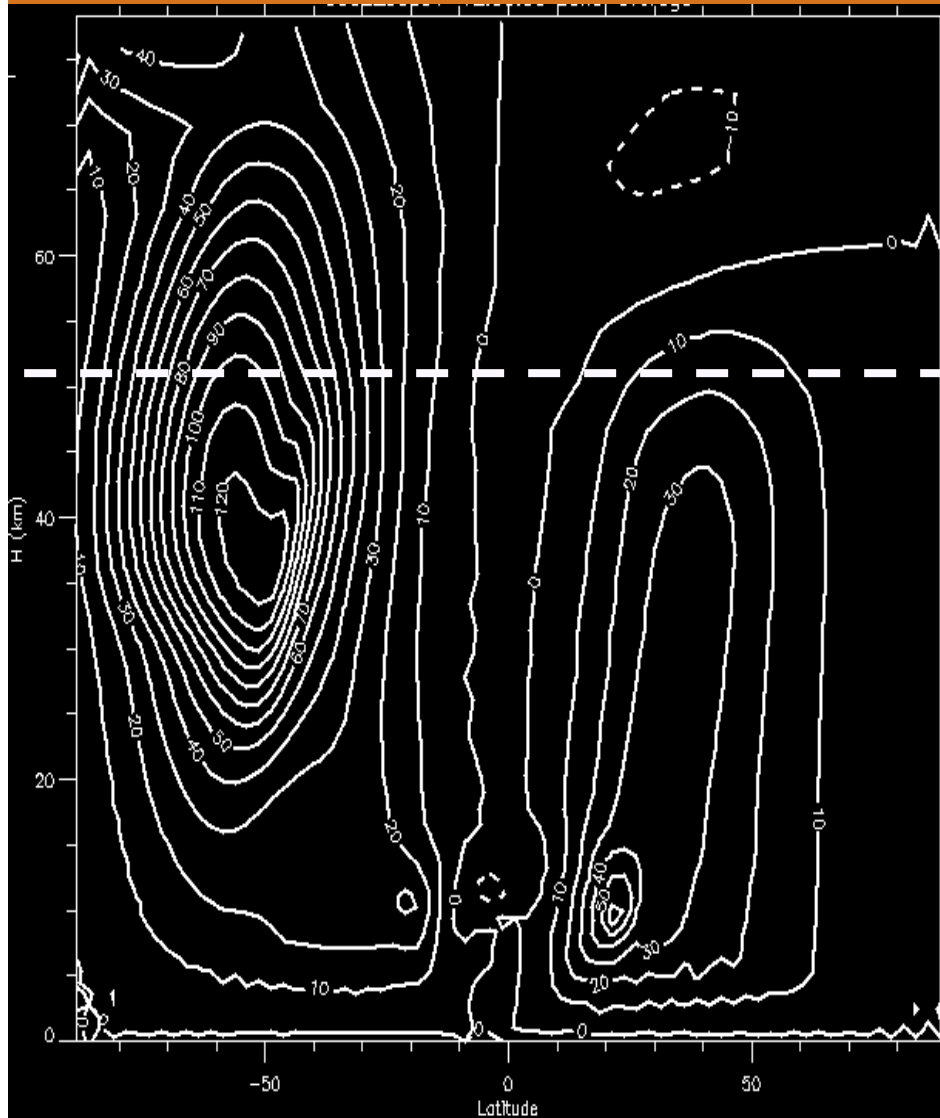
Expected result



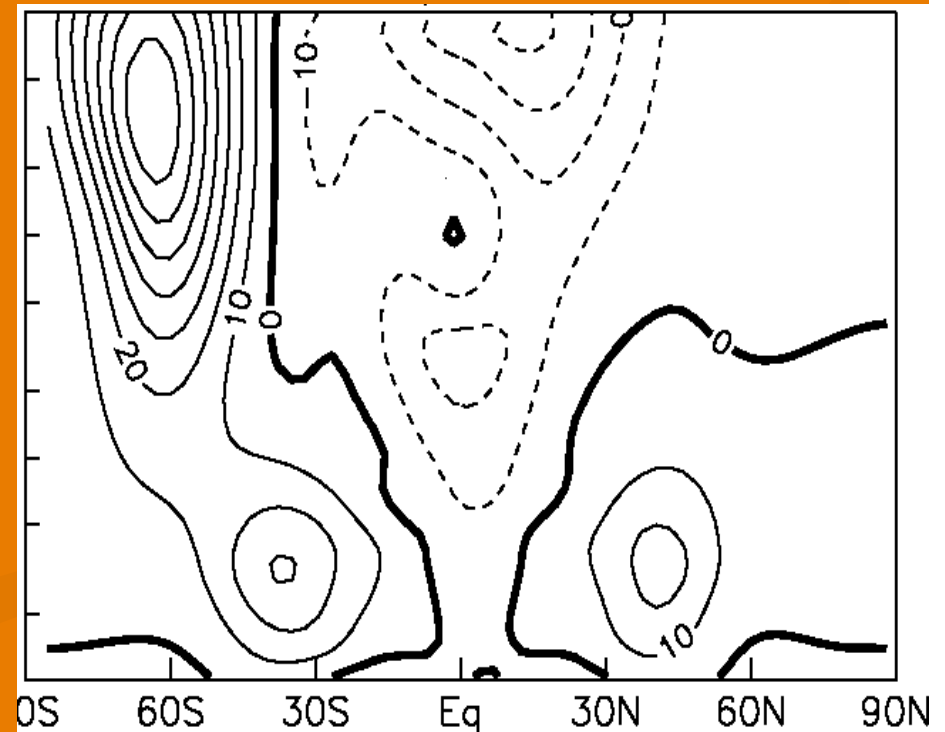


### 3. Polvani-Kushner - in initial stages (up to 380 days, but need average over *last 9000* days of *10000* day experiment)

Zonal mean  $u$  in global WRF at 380 days



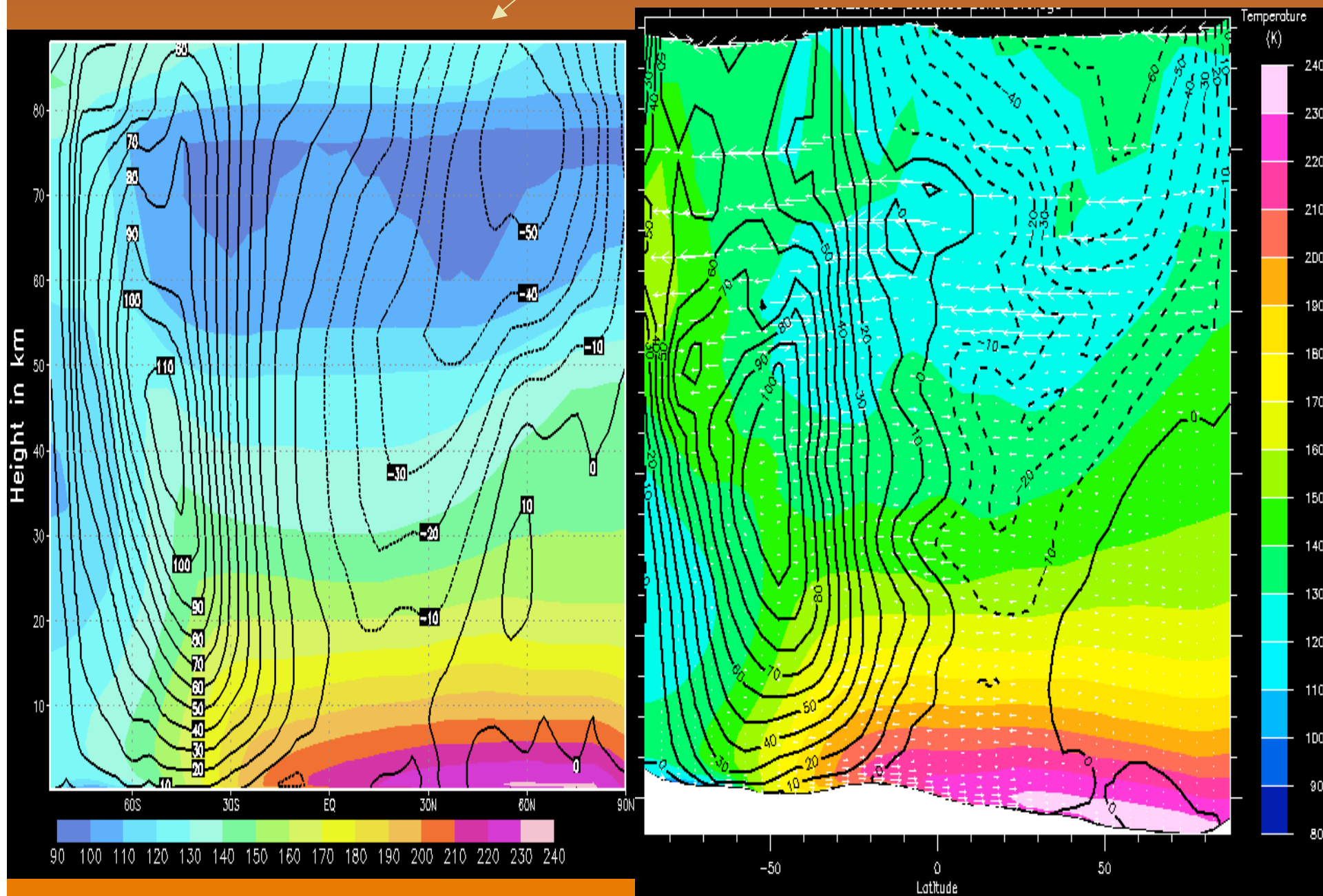
Expected zonal  
mean  $u$  (average  
over last 9,000 days)



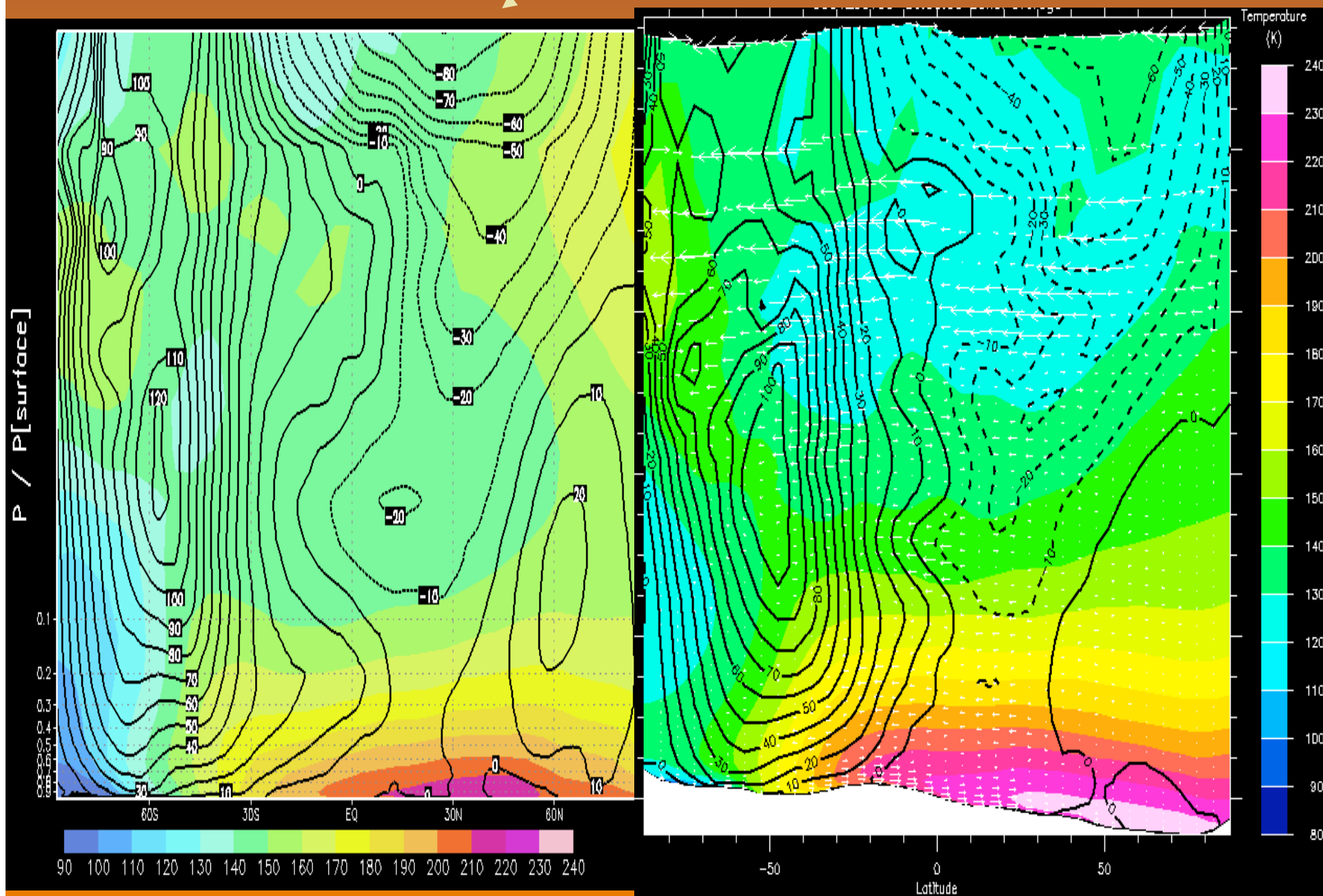
# Results: for Mars (up to 3.)

1. No CO<sub>2</sub> condensation, no atmospheric dust, no topography, diurnally-averaged heating
2. Added topography, diurnal cycle
3. Mars with a realistic (but *prescribed*) atmospheric dust content and with a CO<sub>2</sub> cycle
4. Mars with interactive dust lifting and transport
5. High resolution nests over Hellas, Tharsis, etc.

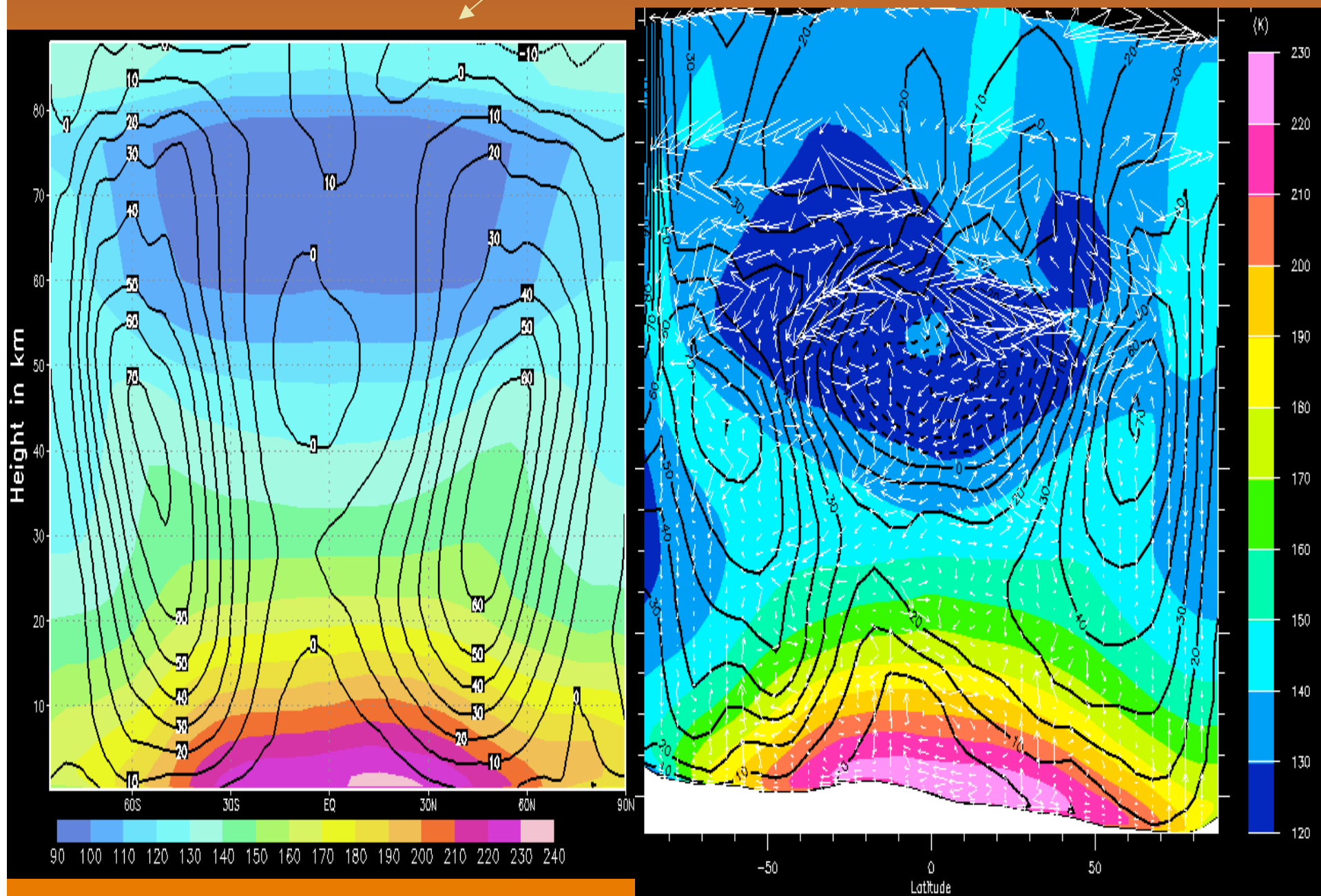
# Northern summer solstice: GFDL Mars GCM and WRF without dust



# Northern summer solstice: Oxford Mars GCM and WRF without dust

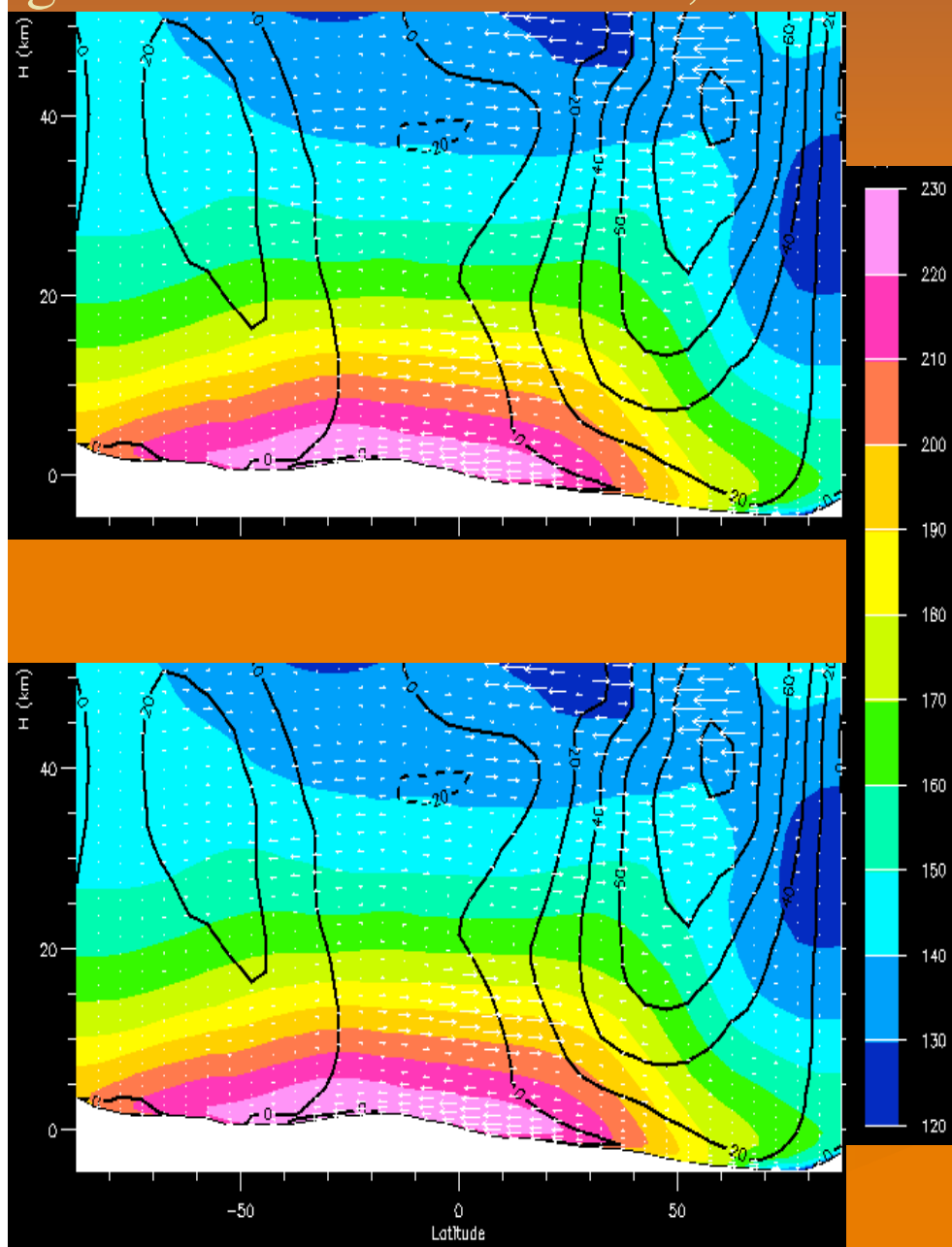


# Southern spring equinox: GFDL Mars GCM and WRF without dust

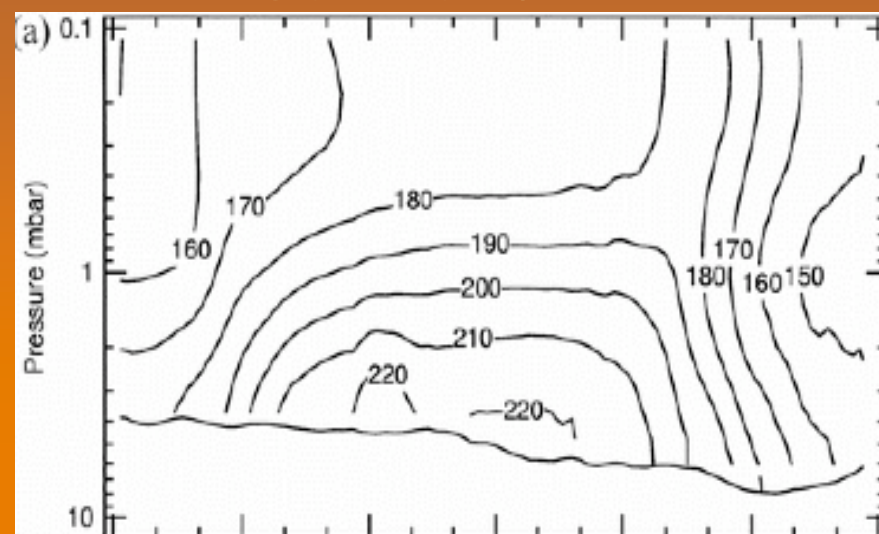




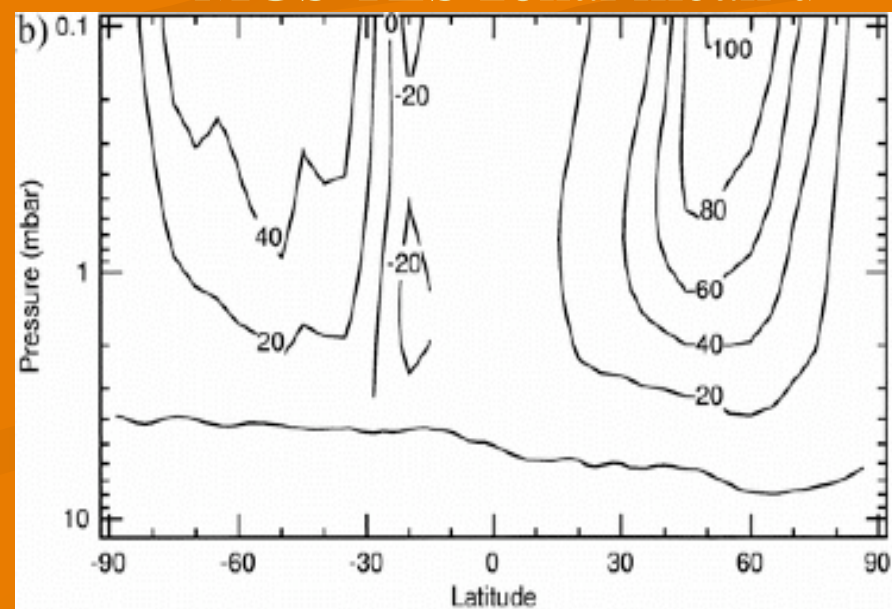
$L_s = 190^\circ$ :  
global WRF zonal mean T, u & wind



MGS TES zonal mean T



MGS TES zonal mean u

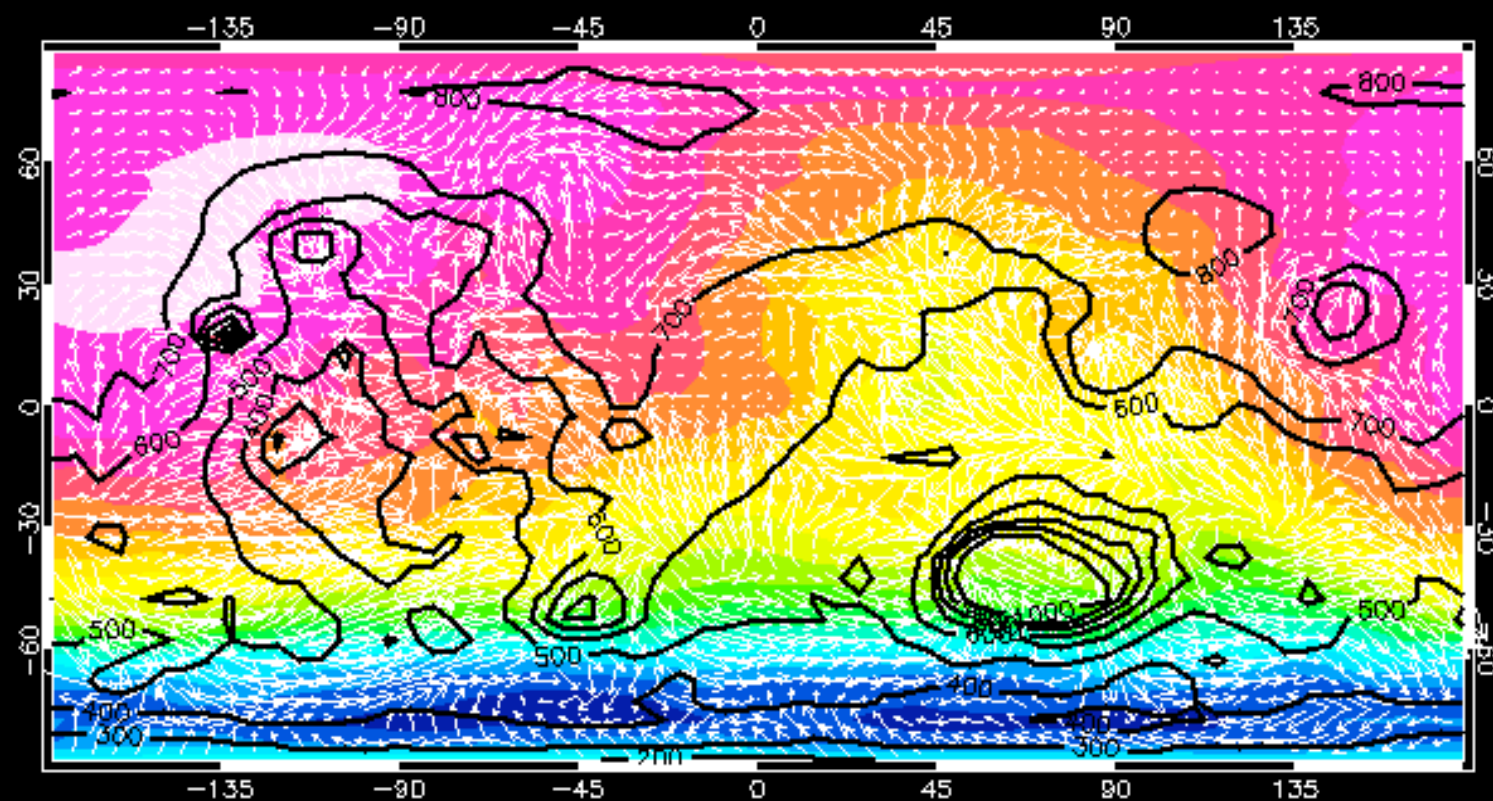




→  
10.00  
Wind  
(m/s)

0001\_00157-00:00:00 K = 39

PRESSURE



# Work completed and to be done

- Slightly ahead of schedule:
  - Completed planetary constants and clock changes
  - Nearly completed global conversion (some issues remaining with diffusion)
  - Beginning conversion to Mars and Titan
- To be done:
  - Demonstration of parallel capability
  - Demonstration of nesting into global domain
  - Completion of planetary conversion
  - Development of polar-stereographic global model